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DEVELOPMENT OF A NEW LASER DOPPLER VELOCIMETER FOR THE AMES HIGH REYNOLDS CHANNEL NO. II

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ABSTRACT

A new two-channel laser Doppler velocimeter developed for the Ames High Reynolds Channel No. II is described. Design features required for the satisfactory operation of the optical system in the channel environment are discussed. Fiber optics are used to transmit the megahertz Doppler signal to the photodetectors located outside the channel pressure vessel, and provision is made to isolate the optical system from pressure and thermal strain effects. Computer-controlled scanning mirrors are used to position the laser beams in the channel flow. Techniques used to seed the flow with 0.5-μ-diam polystyrene spheres avoiding deposition on the test-section windows and porous boundary-layer removal panels are described. Preliminary results are presented with a discussion of several of the factors affecting accuracy.

INTRODUCTION

The laser Doppler velocimetry technique has been developed into a well-established and generally reliable means of obtaining velocity and turbulence measurements in a variety of test flows. Flow-field, turbulent-wake, and boundary-layer data obtained with this technique have been extremely valuable in guiding and verifying numerical calculations for a wide variety of steady and unsteady flows [1-3]. Although the method is considered nonintrusive, it does in fact require the introduction of suitable light scattering particles into the flow. Great difficulties can arise if these particles do not respond with fidelity to changes in flow velocity. This is especially important in the measurement of turbulence. Unfortunately, the in situ verification of scattering particle size distribution is not easily done.

Other challenges encountered in the application of the technique to operating wind tunnels include noise, vibration, thermal, and pressure effects. These effects are especially severe in high-pressure blowdown tunnels. Operational considerations for the mix of sensitive optics and electronics with the normal tunnel procedures and equipment must also be addressed. Safety procedures during the calibration and operation of the commonly used class IV, argon-ion laser must be carefully considered. Handling and injection of the micron-size seed particles must also be well controlled to eliminate health hazards to operating personnel or damage to tunnel equipment.

Consideration of these effects and conditions led to the design of a new laser Doppler system for the Ames High Reynolds Channel No. II. The principal features and operational characteristics of this new system are the subjects of this paper.

FACILITY DESCRIPTION

The High Reynolds Channel No. II, recently placed in operation at Ames Research Center, presents several challenges in the successful use of the laser Doppler technique. This facility, described in Ref. 4 and shown in Figs. 1 and 2, is a transonic blowdown tunnel specifically adapted to two-dimensional airfoil testing and can operate at unit Reynolds numbers up to 30×10^6 per foot.

Facility features specifically intended for airfoil testing include solid, adjustable upper and lower walls to simulate free-air streamlines and porous sidewall suction panels for boundary-layer thinning. These features enable Mach number variations that are caused by boundary-layer growth and thinning to be nullified; they also reduce airfoil sidewall interaction effects. However, constructing a tunnel that incorporates these beneficial features introduces two serious difficulties in the design and use of the laser Doppler velocimeter (LDV). The first major disadvantage is the enclosure of the test section within the pressure shell; this precludes direct optical viewing of the test flow. The second difficulty has to do with the flow-seeding that is required for the LDV measurements because of the lack of naturally occurring particles in the filtered air supply. In this instance, the tunnel flow was seeded with polystyrene latex particles (diameter range from 0.35 to 0.55 μ) in order to satisfy the requirement for controlled particle size and density. Although these particles are ideally suited to the requirements of the LDV system, a problem was anticipated with the porous sidewall boundary-layer-removal-system panels.

These panels are formed of sintered stainless steel and would be rapidly plugged by the seed particles if the particles were present in the tunnel sidewall boundary layer. The solution to these two problems of optical access and seeding deposition in the porous panels will be described later.

LDV SYSTEM

The pressure shell which encloses the test section prevents direct optical viewing of the model and surrounding flow. The approach used to overcome this difficulty was to divide the optical components into two groups. The outer group, consisting of an argon-ion laser (5 W, all lines) and all optics necessary to form the four parallel beams is shown in Fig. 3. One of each pair of beams is Bragg-shifted 40 MHz to eliminate directional ambiguity. This group is mounted on the top of the tunnel outside the pressure vessel. The inner group (Fig. 4) consists of a three-dimensional, computer-controlled scanning mechanism with mirrors, focusing lens, and receiving optics to collect the scattered light from the seed particles. To avoid problems inherent in the operation of photomultiplier tubes in the pressure-vessel environment, the optical Doppler signals from both channels were transmitted, after spatial filtering, through a single, multimode optical fiber that was 10 m long. The signals were then color-separated and viewed by the photomultipliers located outside the tunnel. Negligible signal degradation was observed with this technique [5].

With separation of the optics into inner and outer groups, the tunnel structure unavoidably becomes a component of the optical bench. Although undesirable because of expected noise, vibration, thermal, and pressure strain effects, it was found that these effects could be overcome in the design of the system. Measurements of the vibration of the tunnel pressure vessel at the optics support locations during tests indicated accelerations of the order of 0.1 to 0.2 g in all three axes in the frequency range from 2-5 kHz. These frequencies, being substantially higher than the typical first-bending- mode resonant frequencies of commercially available honeycomb optical tables, are well attenuated by internal construction of the tables. The approach taken was to mount a welded steel frame on six welded supports at the top of the pressure vessel. Brass pads were used to permit relative motion between the pressure vessel and the steel frame to relieve thermal and pressure strain, as shown in Fig. 5. A honeycomb optical table (4 by 8 by 1 ft) was placed on the steel frame using a continuous 0.5-in.-thick felt pad between the frame and the table to decouple and damp high-frequency vibrations. Stop lugs were placed on the steel frame to contain the honeycomb table in the event of a severe seismic disturbance. The honeycomb table, laser, and optics were enclosed by a rigid aluminum cover to isolate the optics from the acoustic field at the tunnel, to protect the system from dust, and to provide a safety shield for the laser beams. The inner, computer-controlled scanning mechanism is mounted on two rails inside the upper wall of the pressure vessel. One rail locates the inner optics with a V-track and grooved wheels. The second rail is flat to permit thermal and pressure strain relief through lateral sliding of the other two wheels. The inner and outer optics assemblies are fixed relative to each other by one of the honeycomb table supports. Access to the laser and optics mounted on the honeycomb table is through six hatches in the cover. For major alignment the entire cover can be rolled back to expose the optics, as shown in Fig. 3b.

The scanning mechanism uses six mirrors to permit scanning of the test flow; direct current servo motors are used with computer control of the primary (vertical) axis. Small motors were used to permit remote adjustment of the scanning mirrors during alignment, and were found to be extremely helpful. Although the optical components used on the honeycomb are straightforward and commercially available, one feature is noteworthy. Provision is made for manual beam path-length adjustment, using two translating mirrors to minimize the errors which occur if the beam waist is not placed at the focal volume [6]. These errors, which arise from unequal fringe spacing in the sample volume, appear as increased variations (fictitious turbulence) in the measured velocities. This error is held to less than 0.5% during a full vertical scan of the test section without adjustment of the path-length compensator.

SEEDING

Air is supplied to the High Reynolds Channel No. II from the 33,000 ft^3 underground air-storage facility. This filtered and dried air supply is stored at 3,000 $lb/in.^2$ and at ambient temperature; it contains negligible particulate matter and must be seeded to permit laser Doppler measurements. Based on experience with Channel No. I, polystyrene latex was selected as the seed material [7]. This inexpensive material is in the form of spherical particles with diameters between 0.35 and 0.55 μ and specific gravity of 1.05.

Although essentially nontoxic, threshold limit values for nuisance dust must be observed, since particles in this size range are a respiratory hazard. Particles in other, more tightly controlled size ranges are also available at much higher cost, but were not needed in this relatively compact forward-scatter system. The combination of size, low specific gravity, low toxicity, and low cost is ideally suited to this

facility. The particles are received in an aqueous solution and are further diluted with denatured alcohol to a concentration of 0.2% solids before injection into the tunnel. Analysis [8] and previous experimental results [1-3] have shown that these particles respond to the motion of aerodynamic test flows with excellent fidelity.

The large tunnel mass flow (800 lb of air per second), limited run time, and need to keep the seed material away from the porous sidewall boundary-layer suction panels presented difficult problems in the design of a suitable injection system. Several configurations were tried at different locations in the tunnel. Excellent mixing and distribution were obtained with multiple atomizing nozzles located in the high-pressure air supply line upstream of the tunnel settling chamber. Seed deposits on the test section windows, however, suggested that plugging of the porous metal panels in the tunnel sidewalls might occur when the boundary-layer-removal system was activated. To circumvent this possibility, an injection nozzle system was designed to provide multiple directed sprays, and it was mounted in the settling chamber entrance section upstream of the first perforated plate. With this arrangement, the seed material was not placed in the tunnel sidewall boundary layers where it could be ingested by the suction system. By varying the pressures of the liquid (seed) and of the air atomizing jets, as well as the geometry of the orifices, a satisfactory seed distribution in the test section was obtained with the design shown in Fig. 6. The opposing liquid jets are atomized by the air jet at each station and carried in overlapping fan-shaped sprays into the settling chamber. It was found that this design was relatively insensitive to tunnel pressures, and that it provided a finely atomized aerosol for a variety of test conditions.

An essential aspect of flow-seeding is the condition of the particles as they pass through the sample volume. Aerosols containing particles of widely varying sizes can introduce serious errors in the measurements. The larger particles are the least likely to respond accurately to flow velocity changes; unfortunately they are the most likely to produce a recorded signal. This is even more probable with degraded or misaligned optics. An aerosol of small, uniformly sized particles is in this sense fail-safe since system degradation terminates data acquisition. Although the polystyrene spheres are small and relatively uniform in size (more so than most other particles), it is important that they be delivered to the test flow as single particles and not as large clusters. In an effort to check the distribution of the particles, samples of the generated aerosols were examined with both optical and electron microscopes. Specimen holders were first covered with transparent tape which had an adhesive on both sides and then were placed in the generated aerosol either on the bench or in the test section of the tunnel during a test.

The captured polystyrene spheres were then coated with a sputtered gold film, approximately 300 Å thick, to provide the conductive layer needed for the electron microscope. Although this work is now in progress, preliminary results indicate that most of the particles are delivered as single spheres when they are finely atomized into a "dry" spray. However, attempts to obtain a high data rate by increasing the liquid flow rate or solid concentration often produced a "wet" spray, with larger droplets containing multiple particles. Clearly, care must be taken even when generating an aerosol from uniformly sized material.

SYSTEM PERFORMANCE

Although the accuracy of LDV measurements is influenced by many factors, it is convenient to separate them into two groups: factors affecting system (instrument) accuracy, and factors affecting overall measurement accuracy. System accuracy is influenced by geometrical measurements of laser beam intersection angle, alignment of the beams relative to the tunnel, positioning accuracy, counter resolution, and other factors generally independent of the particular experiment. Measurement accuracy additionally includes those factors associated directly with the experimental measurement, that is, sampling statistics [9, 10] the effect of sample bias [11, 12], counter performance in the presence of noise, flow variations and unsteadiness, particle distribution, and tracking fidelity. These can all be present and can influence the results. Although a complete discussion of these effects is beyond the scope of this paper, many system accuracy effects have been evaluated.

Measurements were made to determine the laser beam diameters at the intersection (focal volume) using a beam scanner with a 25-μ-wide slit. These measurements indicate a beam width of about 300 μ between the $1/e^2$ (13.5%) amplitude points. Effective focal volume dimensions during measurement, however, are reduced by spatial filtering and synchronous operation since both channels must concur in the observation of the particle. Beam intersection angles θ, appropriate to the expected test velocities, are approximately 2.0°. Absolute system accuracy is directly dependent on this angle since the fringe spacing d is determined by the well-known relation, $d = \lambda/[2 \sin(\theta/2)]$ where λ is the wavelength of the laser beam. Currently, measurements of θ are repeatable to within 1% using various techniques.

Measurements of the alignment of the fringe planes with the tunnel axes is important for accurate measurements of the generally small vertical

velocity component in the presence of a large axial velocity. Geometrical measurements of this alignment indicate an uncertainty in the vertical velocity of about 1% of the axial component. Clearly, more refined means of alignment or calibration are needed. Previously mentioned fringe-spacing variations caused by beam-waist misalignment are held to 0.5% without adjustment. Static (tunnel off) positioning accuracy was found to be about 0.1 mm.

A test to evaluate some of the elements of overall system performance was conducted by substituting an RF oscillator for the photomultiplier tubes to simulate the Doppler signal. As in an actual test the scanner was under computer control and was physically moved to the various commanded positions. These results are shown in Fig. 7 where they are plotted to an expanded scale. The standard deviation of the data in this simulation was about 0.25%. Fringe-spacing variations and counter errors introduced by noise in the Doppler signal will, of course, increase this threshold value in an actual test.

With the development of a satisfactory seeding technique, tests of the complete system have now begun. Satisfactory operation of the system has been demonstrated for tunnel stagnation pressures between 10 and 60 psia.

A plot of the tunnel axial velocity distribution obtained at a location downstream of the nominal test station is shown in Fig. 8. These data were obtained using both channels simultaneously with the system in a fully automatic computer-controlled mode. Three cylindrical rods, used to check the lateral alignment of the seeding nozzles, were in position just downstream of the measuring station. Because of the sensitivity of transonic flows to such disturbances, these preliminary data should not be regarded as illustrative of tunnel flow quality; they are shown only to illustrate operation of the complete system in the tunnel environment.

Tunnel acoustic, vibration, thermal, and pressure strain effects have been effectively suppressed by the system design. The stability of the optical system is excellent and requires minimal adjustment. Often, many tunnel runs over a period of several days may be made without adjustment. The design and operation of the seeding system is, however, a critical element in this facility because of the vented test-section design. The exposed optics in the pressure vessel would be rapidly coated with seed material if the particles were present in the tunnel sidewall boundary layer and circulated through the open sidewall vents.

CONCLUDING REMARKS

A new laser Doppler velocimeter for the Ames High Reynolds Channel No. II has been developed and successfully operated. Several constraints of the facility construction, which places the test section inside a sealed pressure vessel, required a system design approach. Acoustic, vibration, thermal, and pressure strain effects were overcome, and stable optical performance was obtained. A fiber optic was used to transmit the Doppler signal through the pressure vessel shell with excellent results, and a computer-controlled scanning mechanism was used to position the fringe volume automatically within the test flow. Fringe-spacing variations caused by beam-waist misalignment are held to less than 0.5% with a beam path-length adjuster. A seeding system was devised to introduce 0.5-μ-diam polystyrene spheres into the settling chamber. The design of the seeding nozzle restricts particle injection into the sidewall boundary layers; this has effectively prevented contamination of the porous sidewall suction panels and eliminated seed deposits on the viewing windows. It is hoped that the successful operation of this new system will encourage others to use laser velocimetry for applications in difficult environments.

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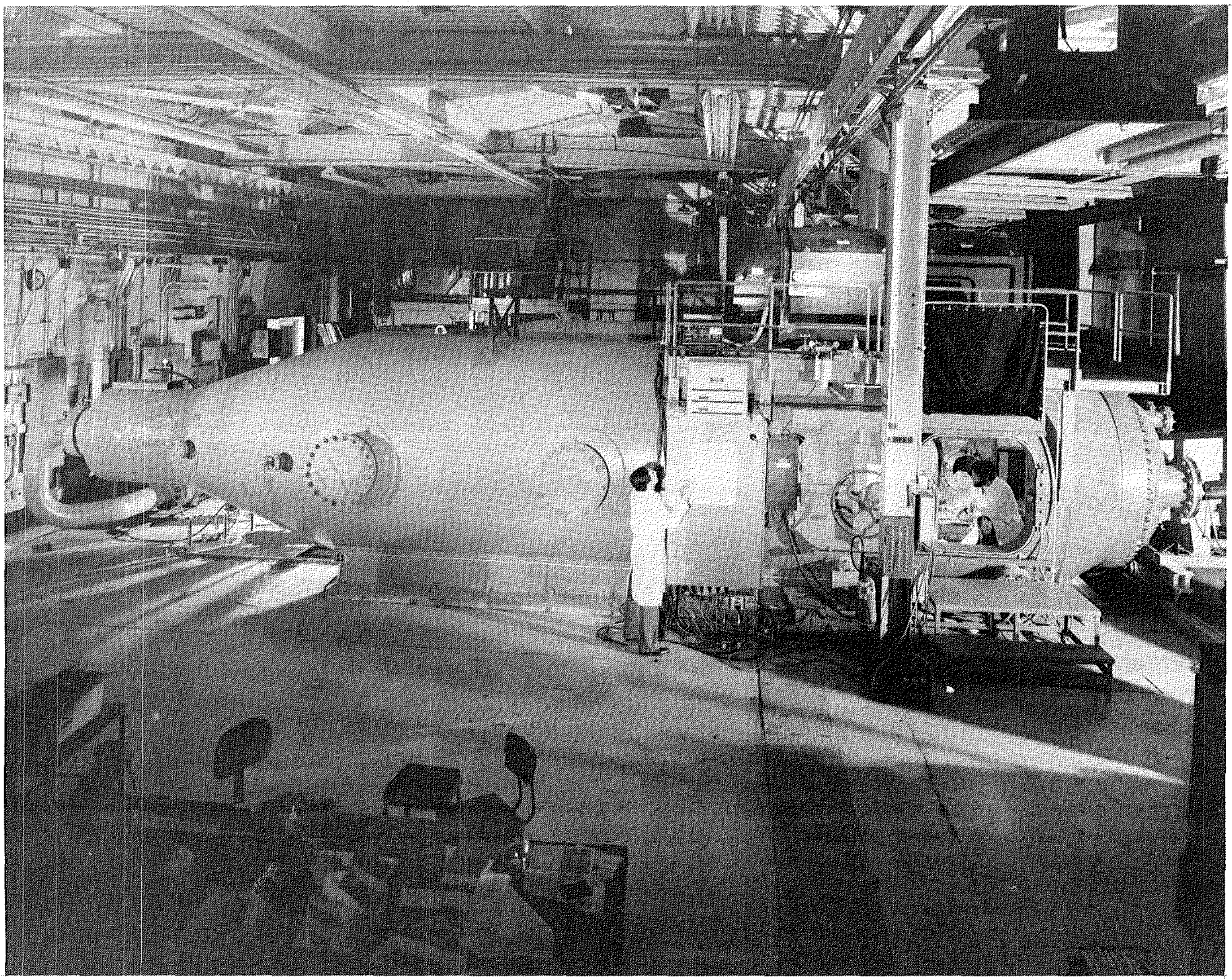


Fig. 1 - The Ames High Reynolds Channel No. II.

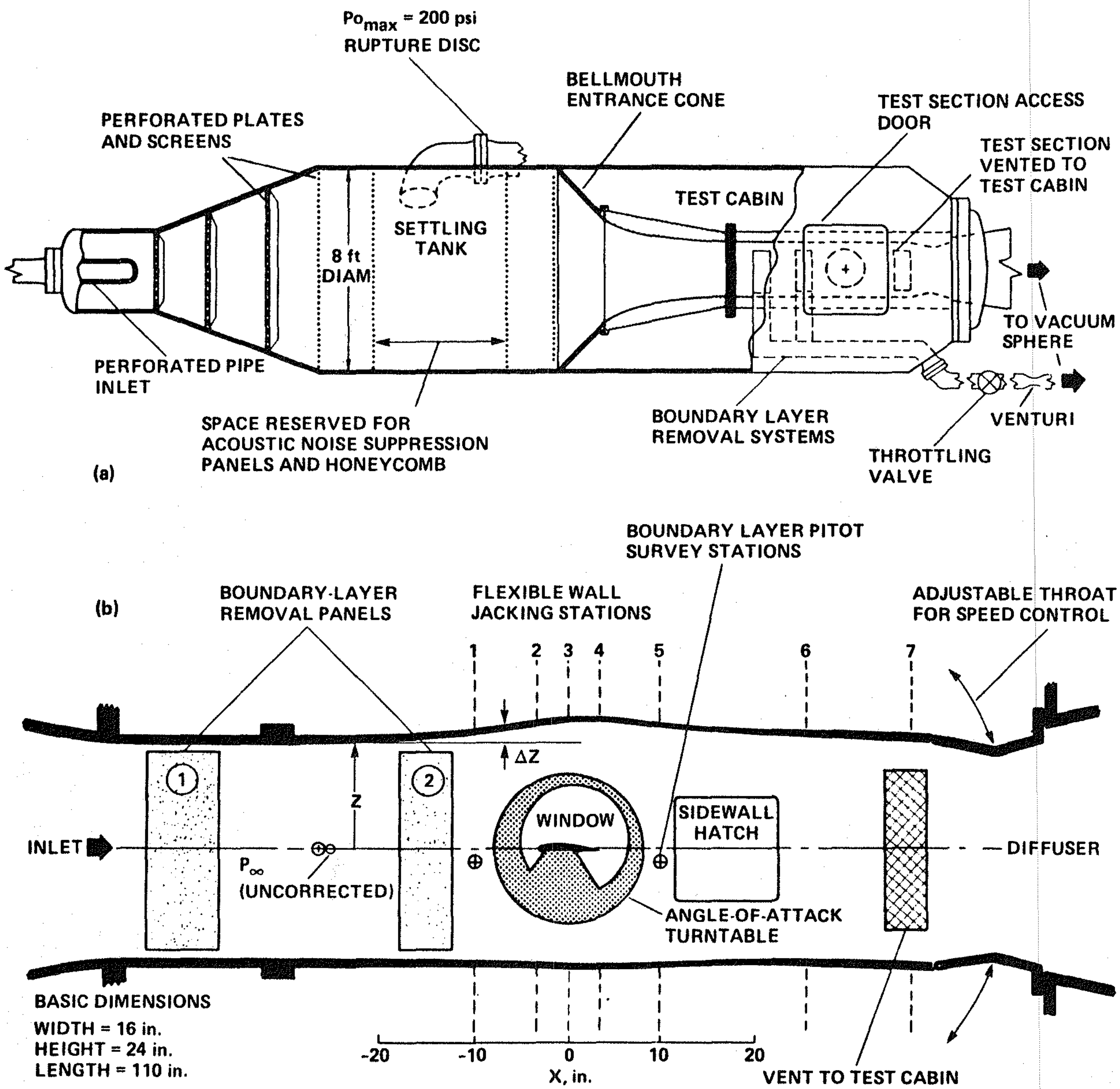
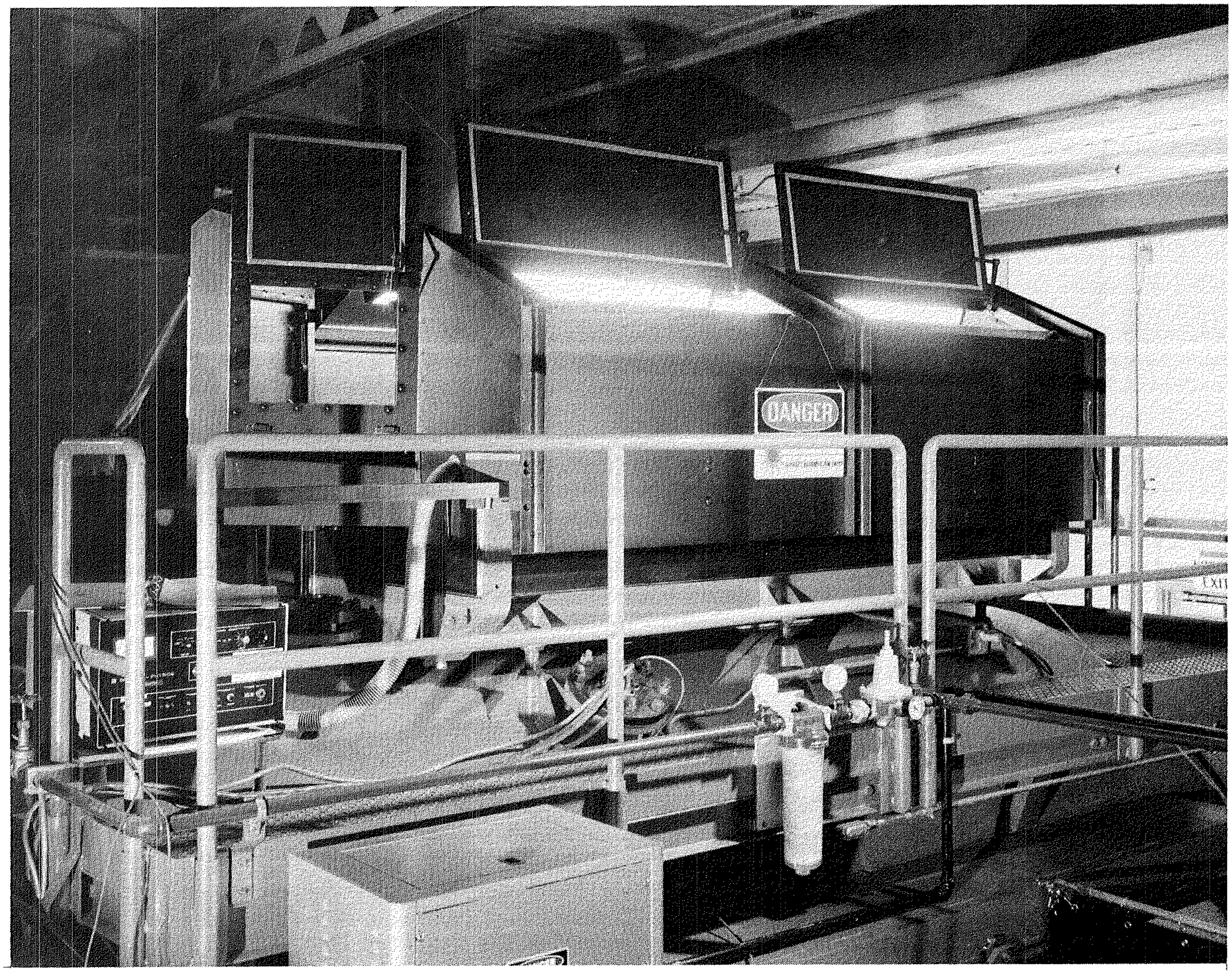
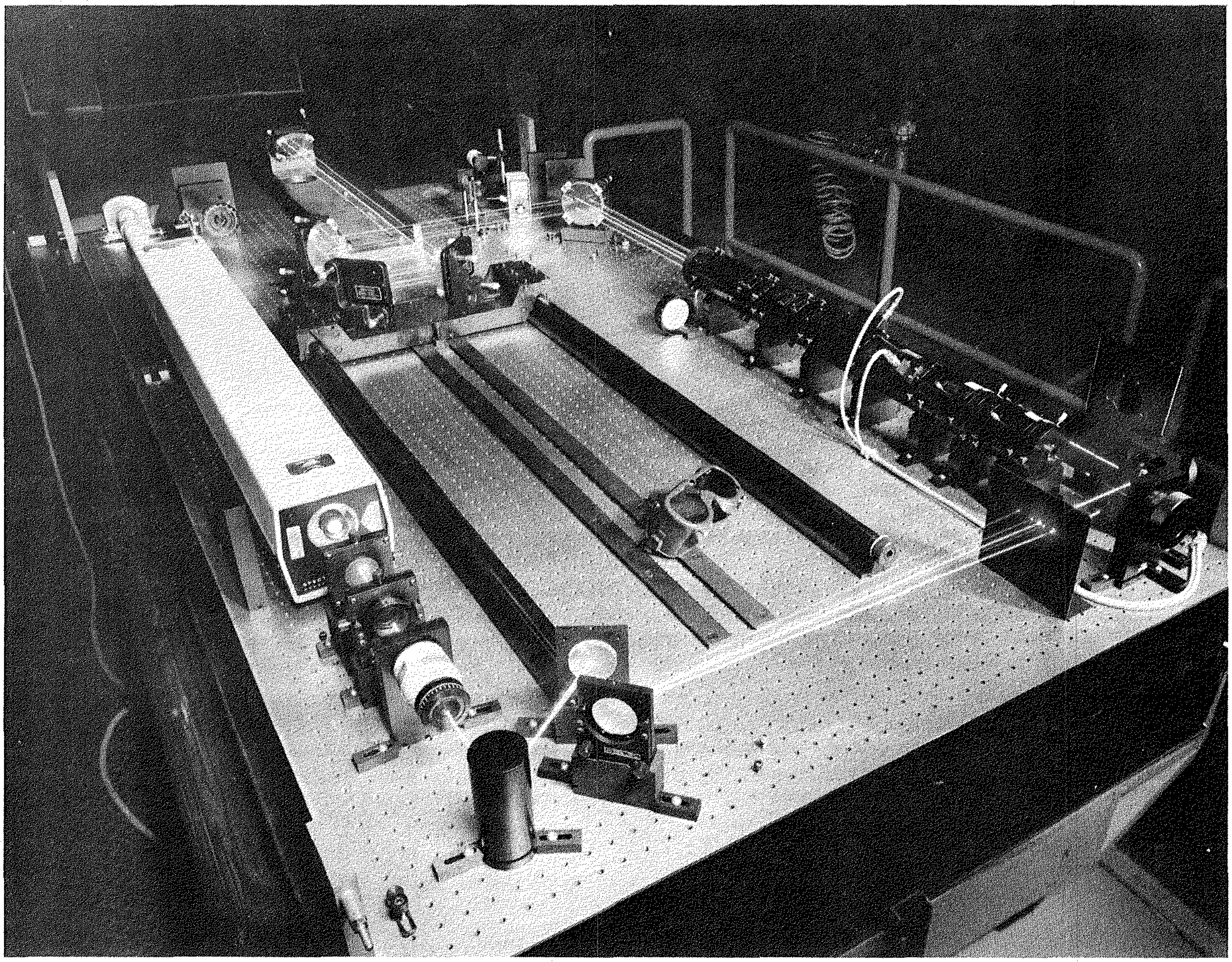


Fig. 2 - Schematic of the Ames High Reynolds Channel No. II. a) Settling chamber and test cabin; b) airfoil test section.



a) View of assembly with cover in place.

Fig. 3 - Outer optics assembly.



b) Cover removed.

Fig. 3 - Concluded.

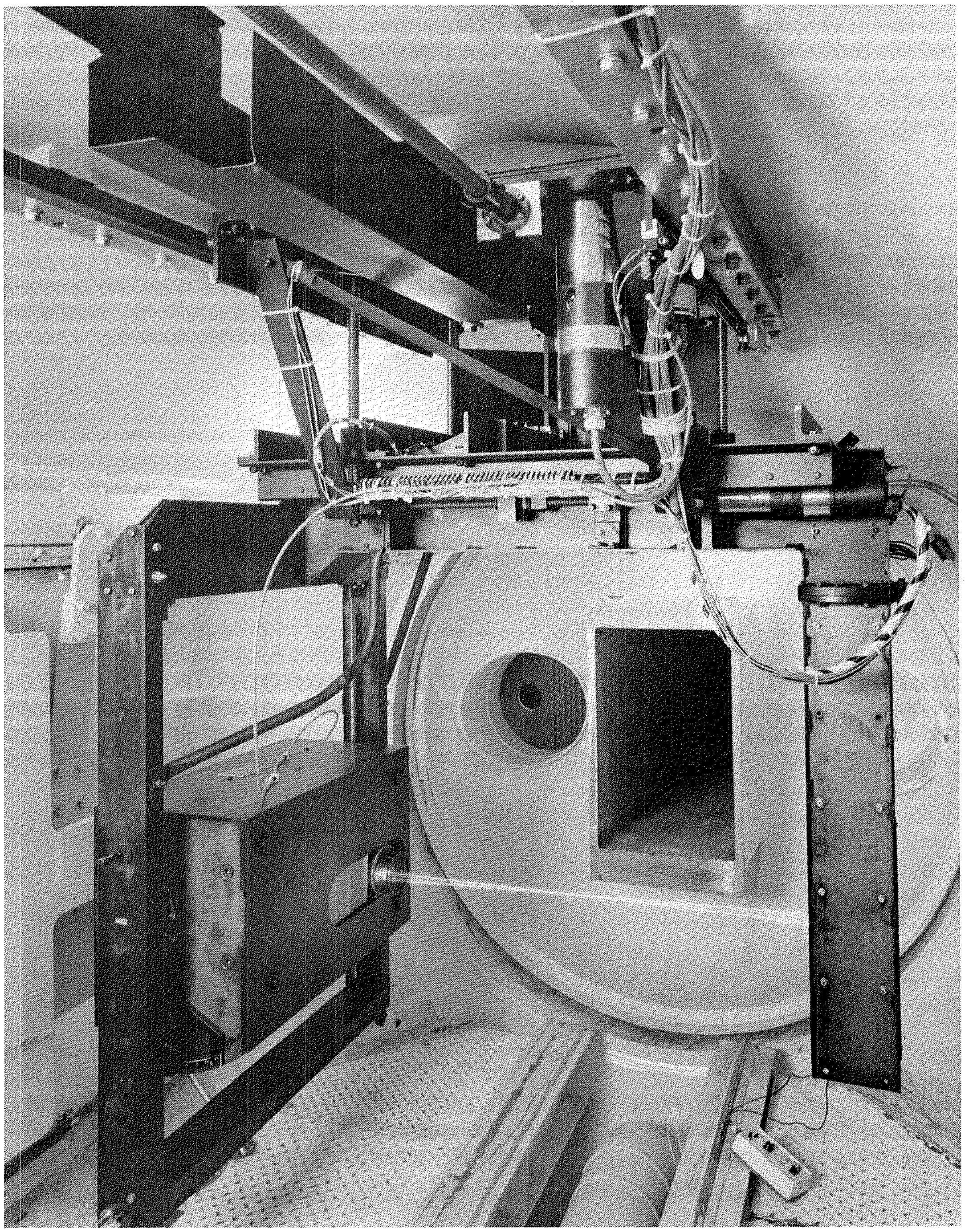


Fig. 4 - Inner optics assembly.

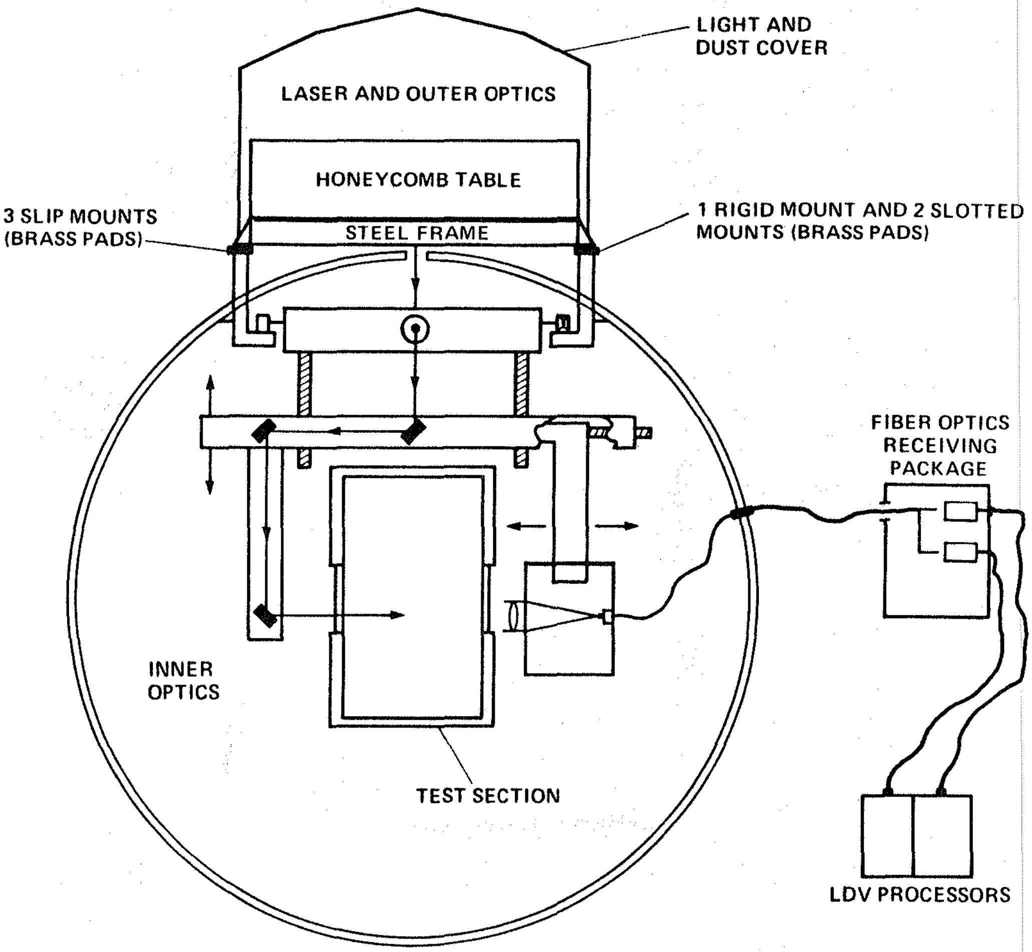


Fig. 5 - End view slowing relationship of inner and outer optics.

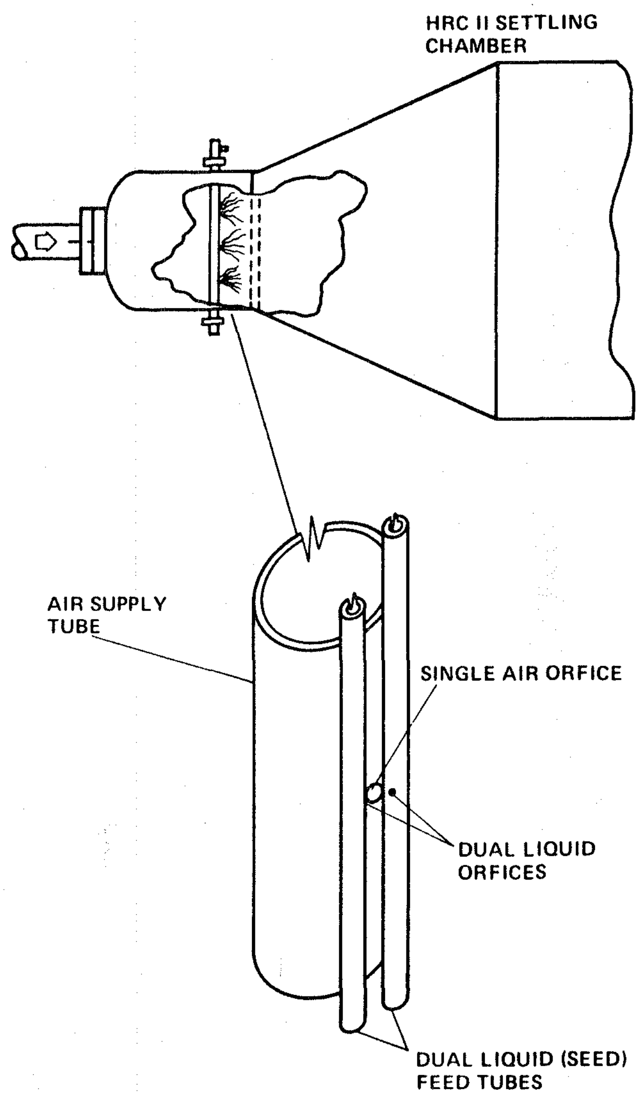


Fig. 6 - Seed-injection nozzle.

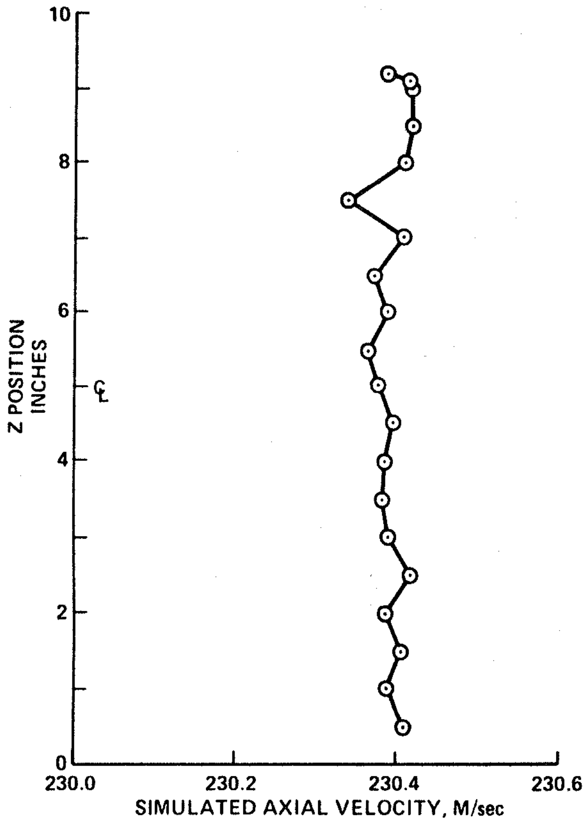


Fig. 7 - Simulated velocity distribution using oscillator frequency source.

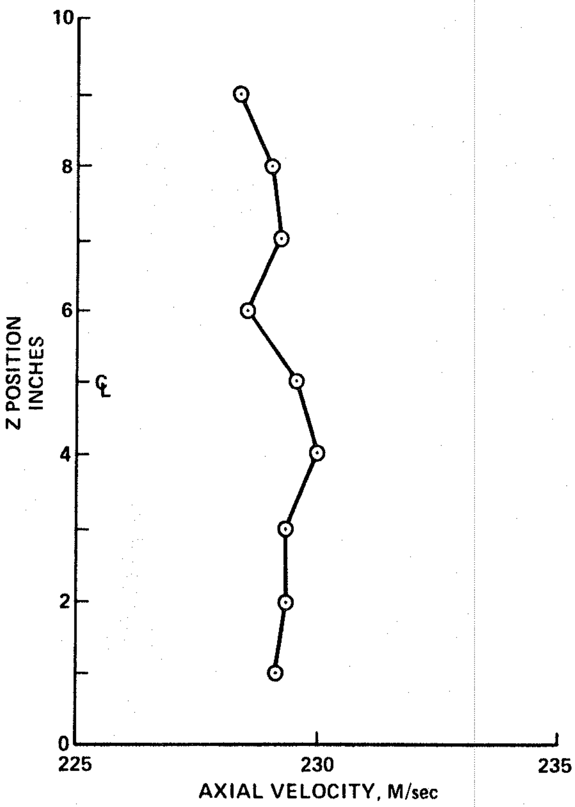


Fig. 8 - Axial velocity distribution measured during tunnel operation.

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15. Supplementary Notes

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16. Abstract

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